

TIME TRANSFER BETWEEN UTC(SP) AND UTC(MIKE) USING FRAME DETECTION IN FIBER-OPTICAL COMMUNICATION NETWORKS

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Abstract

This paper presents recent results from a time transfer method using passive listening and detection of SDH frame headers in fiber-optical networks. The results are based on an experimental fiber-link that is implemented between the national time and frequency laboratories at SP in Borås, Sweden, and at MIKES in Espoo, Finland, with an intermediate connection at STUPI time and frequency facility in Stockholm, Sweden. The total fiber length exceeds 1129 km and is implemented in SUNET (Swedish University Network) and FUNET (Finnish University and Research Network). The two networks are connected via NORDUnet (Nordic Infrastructure for Research & Education) and the links are DWDM-based (Dense Wavelength Division Multiplexing).

Both SP and MIKES maintain local representations of UTC and contribute with clock data to TAI, which gives the opportunity to compare the fiber-based method with those independent methods that are used regularly by the laboratories for the links to UTC. Preliminary results show that a time transfer stability of less than 10 picoseconds is obtained for averaging times of a few hundred seconds. The results also show that the method suffers from daily variations of a few nanoseconds, presumably due to temperature sensitive network equipment and asymmetric fiber paths. Nevertheless, a comparison to GPS carrier phase time transfer over three months shows an rms-agreement of less than 1 nanosecond.

INTRODUCTION

The motivation of developing a fiber-based time transfer method using existing infrastructure is to have access to an alternative and complementary time transfer method. The goal is to make it accessible to regular time and frequency users with precision and accuracy comparable to readily used satellite-based methods. It is well known that time transfer methods using global positioning systems, such as GPS (see e.g. [1] and references therein), are used in a variety of time and frequency applications. For applications requiring extended robustness and reliability, it is often necessary that complementary, backup methods are available with similar precision and accuracy. For instance, in international time metrology, two-way satellite time and frequency transfer (TWSTFT) (see e.g. [1] and references therein) using geostationary

satellites has been used for many years. Also, in recent years, time transfer methods using optical networks have been extensively studied and developed; see for example [2-4]. The fact that optical and radio-based transmission differ in both signal frequency and required infrastructure, make the combination of both types of methods much less vulnerable to intentional or unintentional interruptions.

As a contribution to the robustness and reliability of time and frequency transfer, SP Technical Research Institute of Sweden has developed a novel time and frequency method based on passive listening and detection of SDH frame headers in fiber-optical networks. The method has been studied since 2005 (see e.g. [4-6]), and results based on prototype hardware implemented in experimental fiber-links have shown that time transfer with a precision of a few nanoseconds is achievable over links exceeding 500 km.

This paper presents new results based on new hardware [7] that has been implemented at three clock laboratories, two located in Sweden and one in Finland (see Figure 1). Two of these, SP in Sweden and MIKES in Finland, are national time laboratories that contribute to the international atomic time scale (TAI) and maintain the national representations of UTC, UTC(SP) and UTC(MIKE) respectively. The third laboratory, STUPI, that has its own clock facility with clocks contributing to TAI via SP, is located in Stockholm, Sweden, and is used as an intermediate site for connecting the fiber-links between SP and MIKES. The total transmission distance between these sites exceeds 1129 km.



Figure 1. The red lines symbolize the fiber distance from SP (Borås, Sweden) through STUPI (Stockholm, Sweden) to MIKES (Espoo, Finland) with a total length longer than 1129 km. Approximately half of the fiber length is located on the seabed of the Baltic Sea.

The fiber-links are implemented in the Internet networks SUNET (Swedish University Network) and FUNET (Finnish University and Research Network). The two networks are connected via NORDUnet (Nordic Infrastructure for Research & Education) which provides international connectivity for the Nordic University networks. The complete time-link with all necessary hardware was established in June 2011. Data that was collected from July to October 2011 is used in this study. Before the results are presented and discussed, a brief review of the fiber-method is presented in the next chapter followed by a description of the implemented fiber links. The paper ends with a summary and discussions on future work and developments.

PRINCIPLES OF METHOD AND HARDWARE

The method is based on passive listening and detection of SDH frame headers, presently using an OC-192/STM-64 connection between core IP-routers at a nominal bit rate of 9953 Mbit/s, but is in practice with minor adjustments applicable to any STM line rate or packet-based data transmission network. SDH [8] defines the transmission of packets of data in nominally 125 microsecond-long frames, where each frame starts with a well-defined sequence of A1 and A2 bytes that defines the beginning of a new frame, followed by packet information and finally the payload. The A1A2 sequence is chosen since it is extremely improbable that it occurs anywhere else in the bit stream and can therefore be used as a reference marker for the detection of the start of a new frame. At STM-64, this sequence is 192 A1 bytes followed by 192 A2 bytes.

In the time transfer setup, the reference marker is an electrical pulse which is generated at the detection of a full A1A2 sequence. This marker is measured relative to the local and remote clocks to be compared. To succeed in an accurate time transfer, this operation must be performed both at the bit stream leaving the node, as well as the bit stream arriving to the node, i.e., in a two-way sense [4]. The transmission from a router is governed by a local oscillator (OCXO). The frequency offset and the stability of this clock source for the SONET/SDH framing do affect the performance of the time transfer by its jitter specification of less than 30 picoseconds. This jitter is probably not notable in the present measurements; however, router oscillators could become a limiting component in future systems with increased time resolution.

The transponders in the long haul system use forward error correct (FEC) schemes, like G.709 or advanced FEC, so the clock from the SDH source, in our case the router's internal clock, will be used to phase lock a clock in the transponder of the higher order bit rate needed to carry the payload and the FEC data. Depending on FEC algorithm this can be 15 - 25% higher than the basic SDH/SONET rate. The transponders are also built to the 30-picosecond requirement so improving the timing source might not improve the overall system performance.

Figure 2 shows pictures of the recently developed hardware, the Time Transfer Units (TTU) that are used for this time transfer study. Each TTU contains custom-made printed circuit board (PCB) cards with different tasks and a single-board computer. The unit is 2U high, which is approximately 90 mm. The TTU is described in detail in [7].

DESCRIPTION OF THE TRANSMISSION PATH

The fiber optical transmission path for this time transfer study starts with a router at SP in Borås, Sweden and ends with a router at MIKES in Espoo, Finland. An intermediate location with a router at STUPI in Stockholm, Sweden serves as a bridge between the two end points; see Figure 3. The optical fibers are connected to a DWDM-system (Dense Wavelength Division Multiplexing) with add and drop modules close to the router locations. Two different WDM systems are used; Borås-Stockholm is Ciena Corestream and Stockholm-Espoo is Alcatel. For access and connections to the TTU hardware, passive fiber-optic power splitters are connected to the TX- and RX-path at each router. In the TX-fiber, where the power level is high, 1% of the light is split off to the time analysis circuits of the TTU, and at the RX-fiber, where the power level is low, 10% is split off to the circuits. The 11% loss is only on the drop side of the WDM system where sufficient margins (about 3 dB) are employed. As the transponders do optical-electrical-optical conversion, there is no impact on the system performance as signals are regenerated on both transmit and receive side of the DWDM system.



Figure 2. The recently developed 2U (90 mm) time transfer unit hardware. Front panel and top view (without cover). See [7] for details.

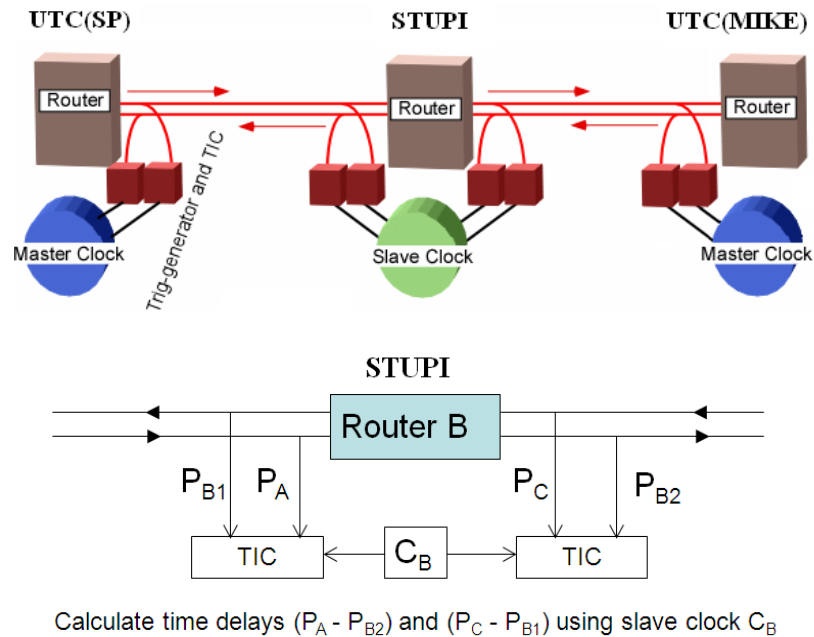


Figure 3. The top figure shows an overview of the connections between the times scales in Sweden, UTC(SP), and in Finland, UTC(MIKE), including the bridge of the intermediate time scale at STUPI. The lower part of the figure is a close up of the intermediate bridge and the slave clock. UTC(SP) to STUPI is one time transfer link and STUPI to UTC(MIKE) is the other one. The bridge at STUPI results in the possibility of calculating the time scale difference [UTC(MIKE) - UTC (SP)].

The transmission path, with a total length longer than 1129 km, is divided into two separate paths with a bridge at the intermediate location and spans over three different network organizations, SUNET, NORUnet and FUNET, in Sweden and Finland. The first path is implemented in SUNET and connects the router at SP to the router at STUPI. This fiber path is longer than 560 km and has nine locations with amplifiers. These include separate dispersion compensating modules for transmit and receive, an OADM (optical add-drop multiplexer) extraction of DWDM bands that are broken into 50 GHz channels with an AWG (Arrayed-Waveguide Grating) and a transponder in each end of the optical path. There are both aerial and underground fiber paths.

The second path is more than 569 km long and also has locations with amplifiers and transponder modules, as well as dispersion compensating fibers. The main difference between the two paths is that the second path is mainly located on the seabed of the Baltic Sea, and it is therefore anticipated that it will not suffer as much from temperature variations along the path as the first path in SUNET. In a submarine cable system, instead of having dispersion compensation modules, the cable itself is made out of different segments with alternating positive and negative dispersion fiber. This might contribute, as discussed below, to the better stability seen there as there are no high-refraction index fibers on spools in “amplifier huts” that change temperature during the day.

The intermediate bridge is located in Stockholm at STUPI. Between STUPI and the location of the DWDM equipment, there is a local dark fiber of about 7 km length where optical circulators are used to put both transmit and receive on the same single fiber, so any path characteristic changes are symmetrical and will cancel out. SP to STUPI connects to one line card of the router and STUPI to MIKES connects to another line card in the same router. The line cards can be operated asynchronously by loop-timing the transmitter to the received clock or use a central clock of the router. The routers are not synchronized to any external source.

RESULTS

The results presented are based on data collected from July to October, 2011 at the three sites SP, STUPI, and MIKES. The TTU-data is collected with a sample period of 1 second, but reduced to 60-second samples using linear least squares analysis of up to 60 samples around the whole minute. One objective of this study is to compare the two national time scales UTC(SP) and UTC(MIKE) using the fiber method and to compare this result against GPS carrier-phase measurements. However, in order to also evaluate the stability of the fiber links and the local time transfer equipment, it was necessary to avoid intentional time scale steering and instead connect the TTU at each site directly to H-masers.

Results will be presented below from three types of time comparisons using three local clocks:

1. [SP(HM1) – STUPI(HROG)]
2. [MIKES(AHM2) – STUPI(HROG)]
3. [UTC(MIKE) – UTC(SP)]

where SP(HM1) and MIKES(AHM2) are two different types of active H-masers and STUPI(HROG) is a steered time scale referenced to an active H-maser. During the assessment period in October, STUPI(HROG) was not steered in order to get as a stable time scale as possible. The third result above was calculated from the first two plus local measurement according to:

$$[\text{UTC(MIKE)} - \text{UTC(SP)}] = \{[\text{UTC(MIKE)} - \text{MIKES(AHM2)}] + [\text{MIKES(AHM2)} - \text{STUPI(HROG)}]\} \\ - \{[\text{UTC(SP)} - \text{SP(HM1)}] + [\text{SP(HM1)} - \text{STUPI(HROG)}]\}$$

where [UTC(SP) – SP(HM1)] and [UTC(MIKE) – MIKES(AHM2)] are local time interval measurements with a short term noise of less than 50 picoseconds.

The results according to items 1-3 as above are presented and discussed separately below. It should be noted that none of the two fiber links has been calibrated, which is an issue for future work and implementation. Thus, in the results presented, an arbitrary constant time offset has been removed from the fiber link data.

1. RESULTS FROM [SP(HM1) – STUPI(HROG)] TIME COMPARISONS

These results are based on the period of October, 2011 when the time scale STUPI(HROG) was not steered and is shown as the red graph in Figure 4. The corresponding Modified Allan Deviation and Time

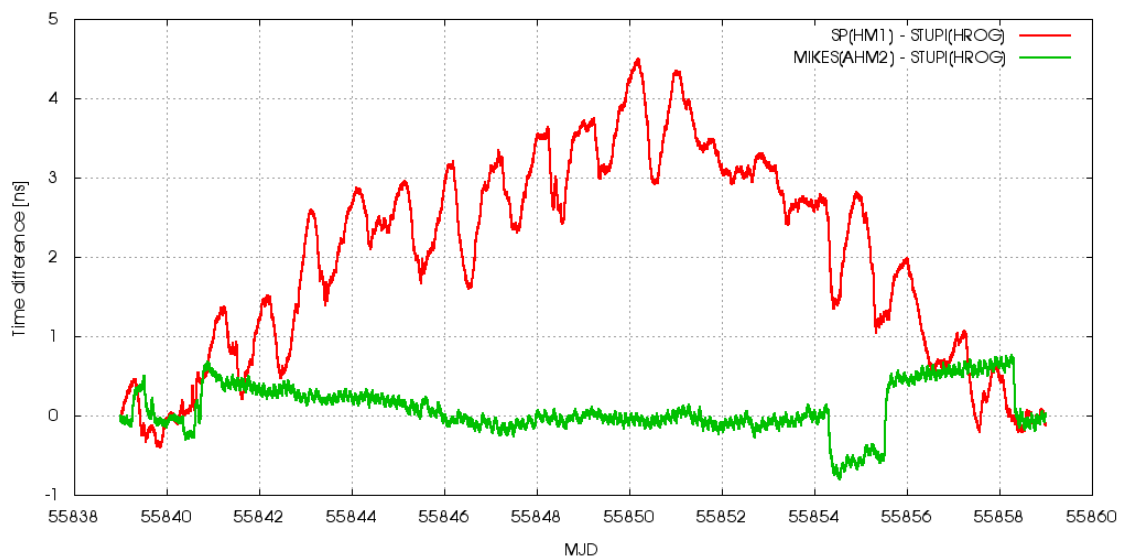


Figure 4. Clock difference [SP(HM1) – STUPI(HROG)] in red and [MIKES(AHM2) – STUPI(HROG)] in green, calculated from respective fiber link as described in the text. A time- and frequency offset has been removed from each graph for clarity. Each data point is a 60-second reduction of 1-second samples.

Deviation are shown as the red graphs in Figures 5 and 6, respectively. It can be seen that the time stability is approaching 5 to 6 picoseconds at an averaging time of about 300 seconds. The stability of the link is also suffering from daily variations with amplitudes of up to about 2 nanoseconds. This instability is presumable due to temperature sensitive network equipment and asymmetric dispersion fiber paths. The frequency stability is nevertheless approaching 3E-15 at one day.

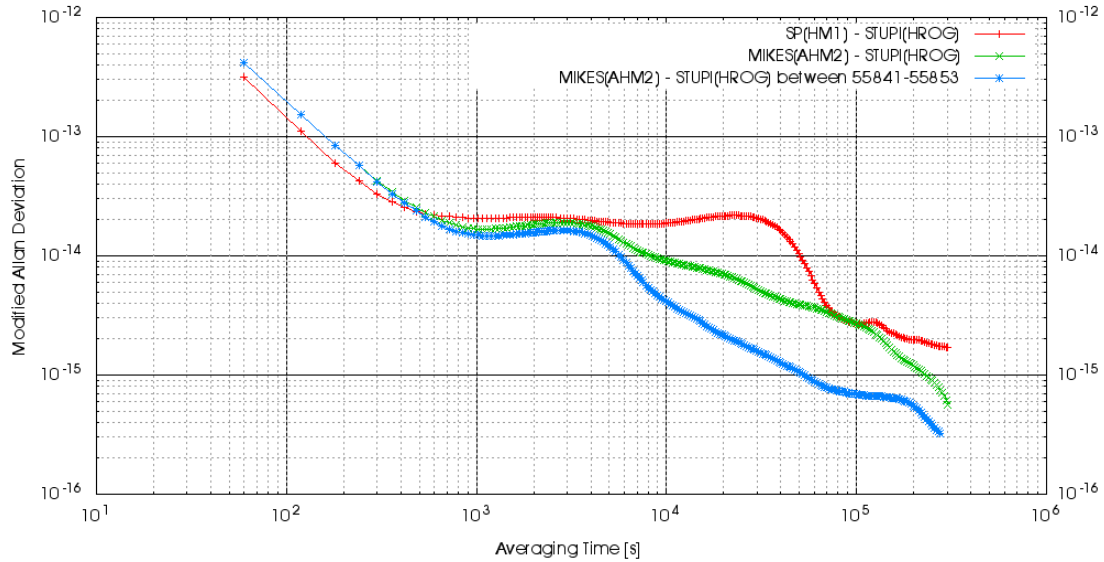


Figure 5. Modified Allan Deviation for the graphs shown in Figures 4 and 7. (Calculated using Stable32 1.47 with frequency drift removed.)

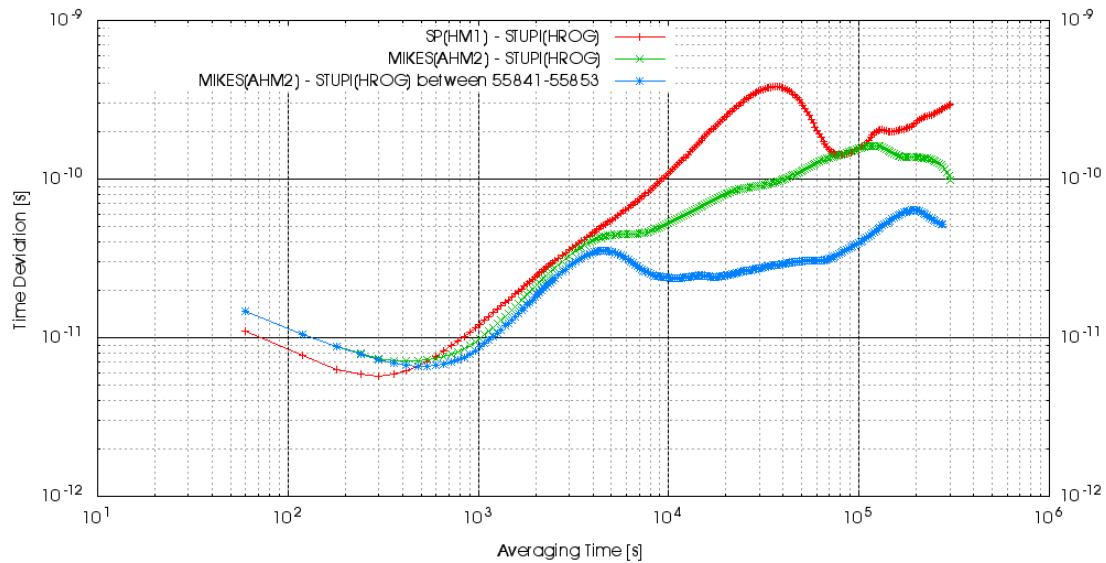


Figure 6. Time Deviation for the graphs shown in Figures 4 and 7. (Calculated using Stable32 1.47 with frequency drift removed.)

2. RESULTS FROM [MIKES(AHM2) – STUPI(HROG)] TIME COMPARISONS

These results are as above based on the period of October, 2011 when the time scale STUPI(HROG) was not steered and is shown as the green graph in Figure 4. The corresponding Modified Allan Deviation and Time Deviation are shown as the green graphs in Figures 5 and 6, respectively. It can be seen that the time stability is approaching 6 to 7 picoseconds at an averaging time of about 600 seconds. The short term stability of this link is somewhat worse than that between SP and STUPI, which also, unless not evaluated, might be an effect of actual clock noise. On the other hand, this link is not suffering from daily

variations which presumably are due to the fact that this fiber path, as discussed above, is mainly located on the seabed of the Baltic Sea.

A few steps are seen, however, in the time comparisons in the beginning and in the end of the data set. These are presently of unknown origin. A time period of 13 days in October for this link is shown in Figure 7. This period is somewhat of a “best result”, presumably with very small impact from environmental effects. The corresponding stability plots are shown in the blue graphs in Figures 5 and 6. The time- and frequency stability is about 30 picoseconds and $8E-16$, respectively, at one day. It is also clear in these plots that a sub-daily variation with amplitudes of up to about 200 picoseconds with a period of 2 to 4 hours affects the stability. This instability is presently of unknown origin and could be both from the fiber links and from the local clocks.

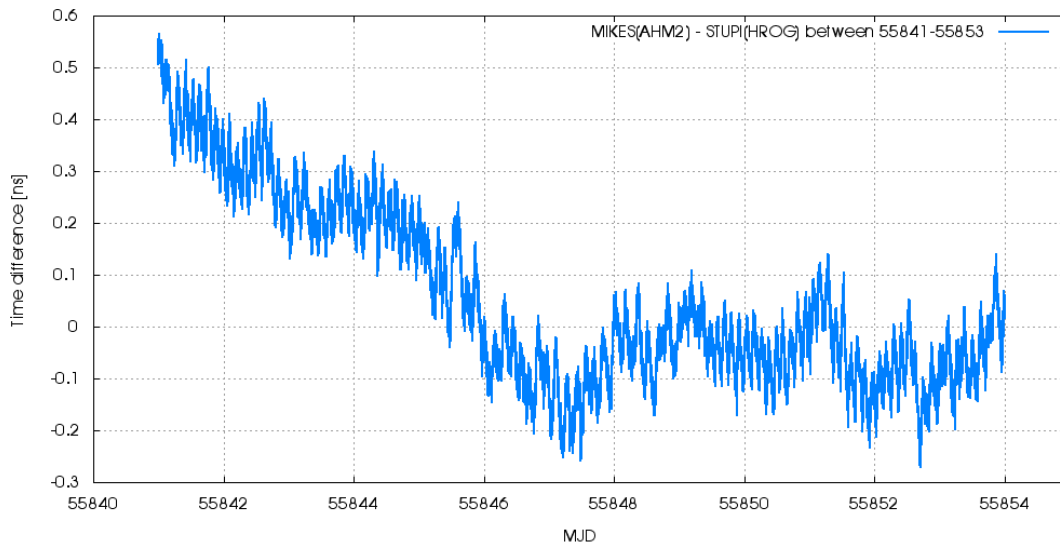


Figure 7. Clock difference [MIKES(AHM2) – STUPI(HROG)] for the time period MJD 55841 to 55853, a sub part of the graph shown in Figure 4.

3. RESULTS FROM [UTC(MIKE) - UTC(SP)] TIME SCALE COMPARISON

These results are based on the three month period of July to September 2011 and calculated according to the above equation of [UTC(MIKE) – UTC(SP)] and shown as the red graph in Figure 8. The GPS carrier-phase result as retrieved from BIPM-data [9] of the same link is shown as the blue graph in the same figure. It is obvious that the daily variation in the fiber link (mainly from the SP – STUPI link) affects the results in the short term. An attempt to reduce the daily variations is shown as the green graph in Figure 8, which is a Kalman-smoothed solution of the fiber link. In addition, to estimate the time scale states, i.e. the time- and frequency offset and frequency drift between the time scales, the Kalman filter is designed to estimate and remove the daily variations modeled as a Gauss-Markov process [10].

The forth, pink graph (crosses) in Figure 8 is the time scale difference [UTC(MIKE) – UTC(SP)] as extracted from the BIPM Circular T of July, August and September [11]. The Circular T points, every fifth day, follow the GPS carrier-phase solution with minor offsets, remembering that SP is using the satellite-based TWSTFT-technique for the link to UTC.

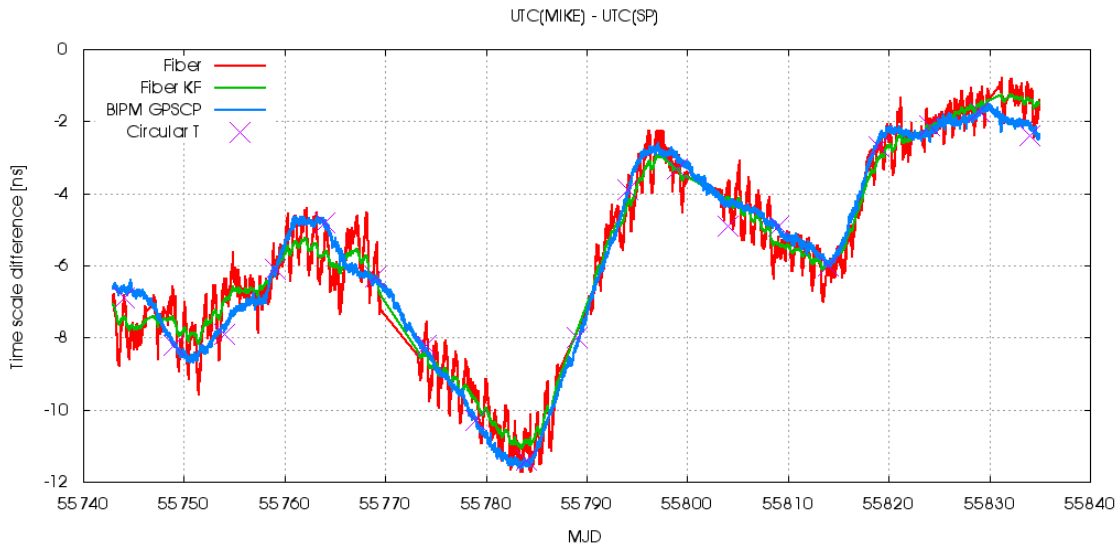


Figure 8. Time scale difference [UTC(MIKE) – UTC(SP)]. Fiber link with arbitrary constant time offset in red, Kalman smoothed fiber link in green, GPS carrier-phase (GPSCP) link as retrieved from BIPM in blue, and BIPM Circular T data in pink crosses.

The difference between the fiber and GPS carrier-phase solutions of [UTC(MIKE) – UTC(SP)] is shown as the red and green graphs in Figure 9 for the raw- and Kalman-smoothed fiber solution, respectively. The RMS-difference between the methods is 0.64 nanoseconds.

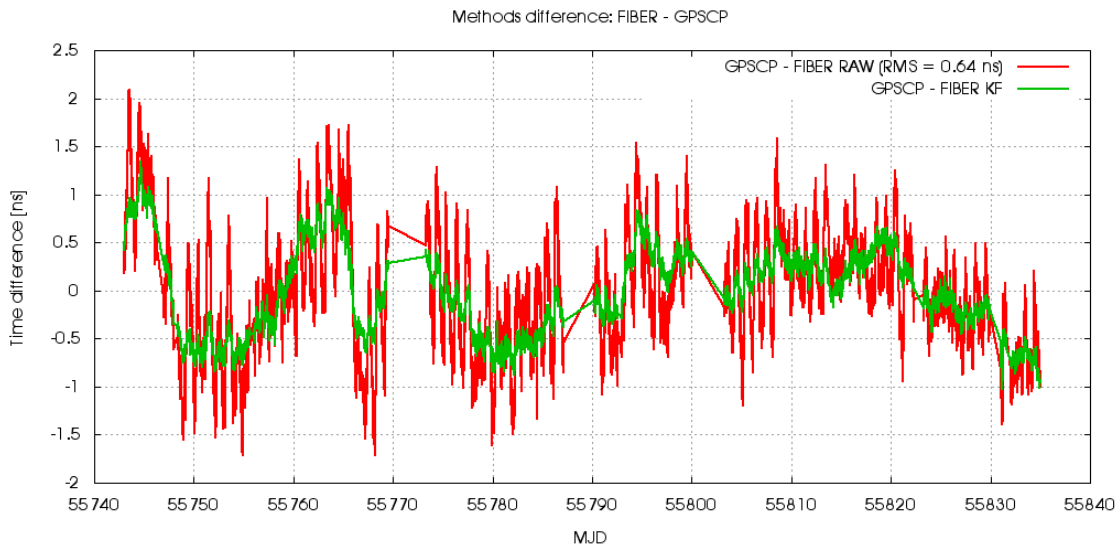


Figure 9. Difference between the fiber- and GPS carrier-phase (GPSCP) solutions of [UTC(MIKE) – UTC(SP)] as shown in Figure 8, in red for the raw fiber solution and in green for the Kalman-smoothed fiber solution.

CONCLUSION AND FUTURE WORK

Time transfer using a method based on passive listening and detection of SDH frame headers in a fiber-optical link has been demonstrated. The link has been established since June, 2011 in three computer networks (SUNET, FUNET, and NORDUnet) in Sweden and Finland with a total length exceeding 1129 km.

It has been shown using recently developed time transfer hardware, installed at the national laboratories for time and frequency in Sweden and Finland, that a time stability of 6 picoseconds can be achieved at an averaging time of about 300 seconds and a frequency stability of less than $1\text{E-}15$ at about one day. A comparison with GPS carrier-phase for the time link [UTC(MIKE) – UTC(SP)] shows an rms-agreement of less than 1 nanosecond.

Future work includes a detailed assessment of temperature dependent daily variations in the link, the development of a method for system calibration, as well as an improvement of local data collection- and analysis software. It also includes a conversion of this method from an experiment to a production model that is automated and fully redundant, as well as finding methods to handle changes in fiber lengths due to operational maintenance and repair of fiber cuts.

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